GRENAC's Latest Activities in Nuclear Reactor Development

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GRENAC Weekly Meeting

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GRENAC - Gupo de Reações Nucleares, Aplicações e Computação

GRENAC's Nuclear Reactors Branch:

- Dr. Airton Deppman – Coord.
- Paula Matuoka, PhD.
- Renato Nunes, MSc.
- Dr. Giovanni de Stefani (IPEN).
- Dr. Pedro Rossi (UFABC).

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Previous work:

- **Study of nuclear reactions involving heavy nuclei and intermediate- and high-energy protons and an application in nuclear reactor physics (ADS)**
  Paula Matuoka (IFUSP, MSc), 2016.
- **High energy nuclear reactions ("Spallation") and their application in calculation of the acceleration driven systems (ADS)**
  Pedro Rossi (IPEN, PhD), 2011.
- **An alternative proposal for a hybrid reactor (subcritical facility coupled with an accelerator)**
  Sérgio Pereira (IPEN, PhD), 2002.

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New research proposal (2017):
ADS Nuclear Reactor using thorium cicle.
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Year	Who	Main subject	Nuc.Fuel	E_p (MeV)	Target	Model/Codes
2002	S.Pereira	ADS/Subcritical reactor	^{232}Th/^{233}U	500	Pb	MCNP4
2011	P.Rossi	Spallation source				CRISP, MCNPX
2016	P.Matuoka	Nuc.Reac./ADS Reactor	^{238}U/^{239}Pu	1200	Pb	CRISP, MCNP5, Serpent
2019*	R.Nunes	ADS Reactor	^{232}Th/^{233}U			CRISP, MCNPX, Serpent

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Starting point:
- Interactions of protons with matter.
- Spallation neutron source: thick target.
- ADS nuclear reactor from previous work (Matuoka, 2016).

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Preliminary results to be presented by Paula Matuoka at the XL Brazilian Meeting on Nuclear Physics (Campos do Jordão, 3-7 Sep/2017).

Spallation neutron source

Previous work (Matuoka, 2016):

- Target: liquid LBE cylinder (H = 3m; D = 40cm).
- Neutrons – spatial distribution: isotropic around the target.
- Neutrons – energy distribution: evaporation (Weisskopf) spectrum.
- SIMPLIFIED!

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New approach (possible lines):

- Atomic processes (dE/dx): spatial and energy distribution of protons inside the target.
- Transport of high-energy particles in matter.
- Target design: optimized dimensions.
- MORE REALISTIC neutron distributions (spatial and energy).

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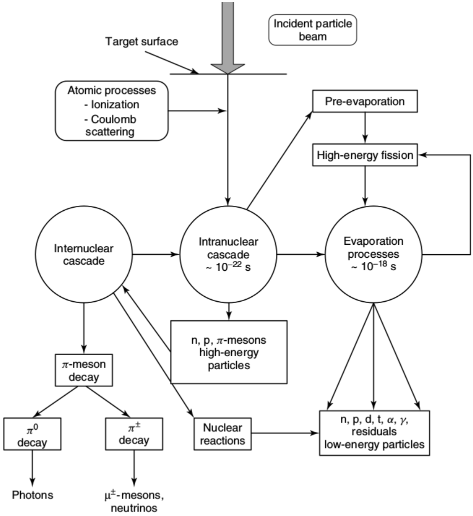
New questions:

- Would the neutron multiplicity increase or decrease?
- Would it change significantly the fragment production?

Spallation neutron source



Reference:
Handbook of Spallation Research: Theory, Experiments and Applications.

D.Filges & F.Goldenbaum, Wiley, 2009 (p.22).

Figure 1 : Spallation: particle/fragment production.

Bethe-Bloch Formula – Energy loss by collision (dE/dx)

For massive charged particle ($m_0 >> m_e$).

$$-\frac{dE}{dx} = \frac{2\pi n z^2 e^4}{m_e v^2}\left\{\ln\left[\frac{2 m_e v^2 W_m}{I^2(1-\beta^2)}\right] - 2\beta^2 - \delta - U\right\} \quad (1)$$

Where:

m_p	: incoming particle mass
$v = \beta c$	: incoming particle velocity
z	: incoming particlecharge number
m_e	: electron mass
n	: number of electrons per cm^3
I	: mean excitation energy of the atoms of the material
W_m	: maximum transferable energy from the incident particle to atomic electrons
δ	: correction for density-effect.
U	: shell correction term (for very low incoming kinetic energies).

Reference:

Principles of Radiation Interaction in Matter and Detection. C.Leroy & P.Rancoita, World Scientific, 2009 (p.32).

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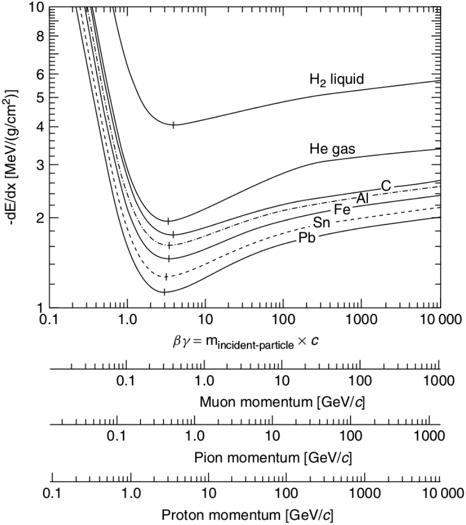

Figure 2 : Bethe-Bloch Formula.

Bethe-Bloch Formula – Energy loss by collision (dE/dx)

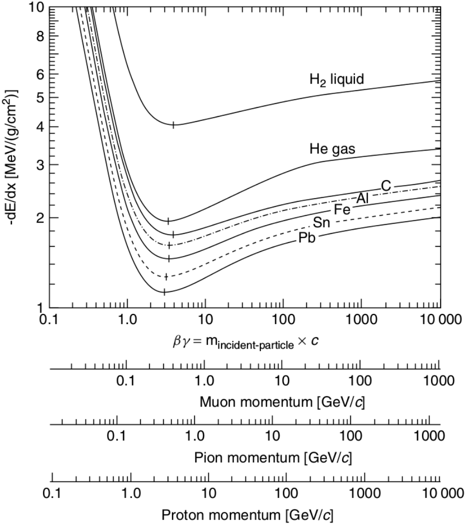

Figure 2 : Bethe-Bloch Formula.

Ex: protons ($m_0 = 938.3$ MeV/c^2).

$$p = \sqrt{E_k(E_k + 2m_0c^2)}/c \qquad (2)$$

Lead: $\rho_{Pb} = 11.34$ g/cm^3

E_k (GeV)	p (GeV/c)	-dE/dx (MeV/(g/cm^2))	-dE/dx (MeV/cm)
1.0	1.7	1.3	14.8
1.2	1.9	1.2 ($\sim$mip)	13.6

Reference:
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D.Filges & F.Goldenbaum, Wiley, 2009 (p.35).

Range

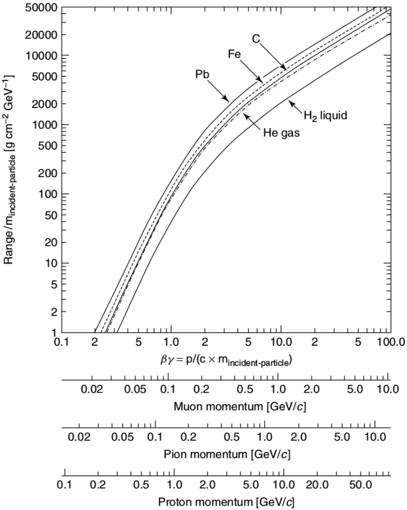

Figure 3 : Range.

Range

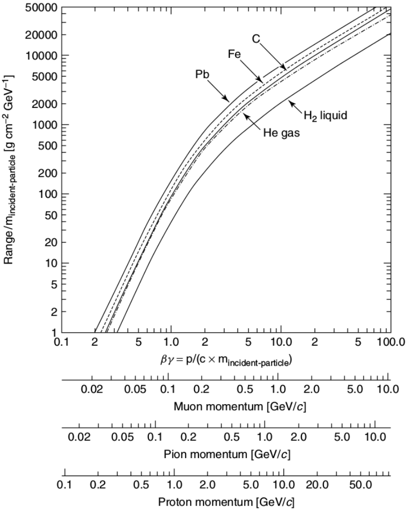

Figure 3 : Range.

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Range [cm] $=$ Range$/m_p \times m_p/\rho$

E_k (GeV)	p (GeV/c)	Range (g/(cm^2.GeV))	Range (cm)
1.0	1.7	500	41
1.2	1.9	700	58

Reference:
Handbook of Spallation Research: Theory, Experiments and Applications.

D.Filges & F.Goldenbaum, Wiley, 2009 (p.35).

Nuclear range

G. Barros et al. **Neutron production evaluation from a ADS target utilizing the MCNPX 2.6.0 code.** Brazilian Journal of Physics, 40(4), 414-418 (2010).

Energy loss:
Nuclear/Electronic $\sim (A/Z)E^{0.75}$.

1 GeV proton on lead:

- Electronic range: 45 cm
- Nuclear range: 16 cm
- Nuc/Elec $\sim$ 2.5

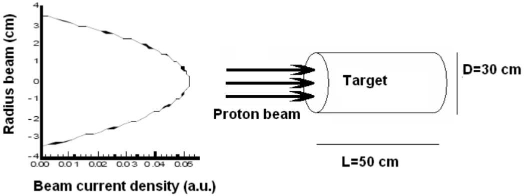

Figure 4 : Spallation target and beam profile.

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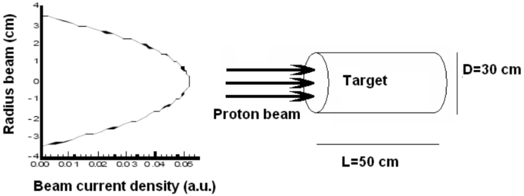

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MCNPX User's Manual Appendix E: Spallation source tutorial.

Particle transport simulation

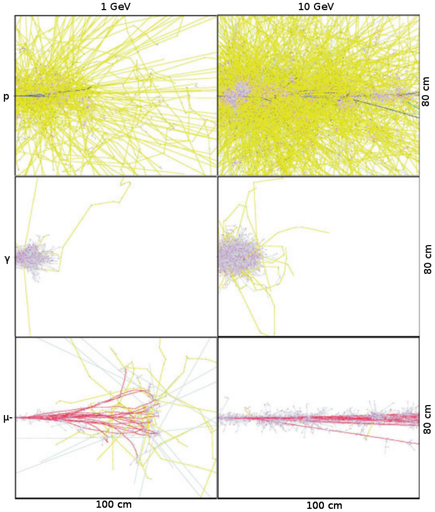

Figure 5 : Particle showers on lead.

GEANT4 Simulation:
Hadronic interactions, multiple scattering, bremsstrahlung, ionization, pair production, photo-Compton effects, electroweak decays, and annihilation.

Color label:

Protons	: blue
Neutrons	: yellow
Photons	: gray
Muons$^-$	: red
Electrons$^-$	: magenta

Reference:
Handbook of Spallation Research: Theory, Experiments and Applications.

D.Filges & F.Goldenbaum, Wiley, 2009 (p.187).

Particle transport codes and models

	MCNPX	PHITS	FLUKA	GEANT4	MARS
Particles	34	38	68	68	41
Energy loss	Bethe-Bloch	id.	id.	id.	id.
Scattering	Rossi	Moliere	Moliere	Lewis	Moliere
Straggling	Vavilov	Vavilov	custom	Urban	custom
Cherenkov	No	No	Yes	Yes	No
Low-energy neutrons	Cont. ENDF	Cont. ENDF	72 multi-group	Cont. ENDF	Cont. ENDF
Low-energy protons	Cont. ENDF Models	Models models	Models Models	Models Models	Models Models
Used models e.g.,	Bertini ISABEL INCL/CEM LAQGSM FLUKA89	Bertini GEMJAM JAM/JQMD >3GeV	PEANUT DPMJET Glauber neutrinos	Bertini INCL ABLA GEM GHEISHA	CEM LAQGSM DPMJET
Other features					
Delayed decay of	$n's/\gamma's$	$n's$	$\beta's$ / $\gamma's$	$\alpha's/\beta's/\gamma's$	$\gamma's$
Eigenvalue	Yes	No	No	No	No
Burn-up	Yes	No	No	No	No
Fields E, B	Yes	Yes	Yes	Yes	Yes

Figure 6 : Code comparison. Reference: **Handbook of Spallation Research: Theory, Experiments and Applications**. D.Filges & F.Goldenbaum, Wiley, 2009 (p.211).

Status

Status (now):

- Study on Bethe-Bloch implementation - Paula & Renato
  Proton energy loss for different depths of the target $\rightarrow E_i \rightarrow$ CRISP
- MCNPX on PC - ok!
- Installing MCNPX on GRENAC's cluster - ongoing!
- Reviewing previous ADS design & materials - Paula & Giovanni
  1. Thorium based PWR: burnt fuel $\rightarrow$ ADS.
  2. $^{232}Th/^{233}U$ Breeder.
- Next meeting in $\sim$ 10 days.

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To think about:

- Coupling CRISP to a particle transport code (GEANT4?).

Thank you!